Emergent Lorentz Invariance

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Based on

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+work in progress

w/ S Sibiryakov, G Bednik

Focus Week on Gravity and
Lorentz Violations, Kavli-IPMU

February 20th 2013

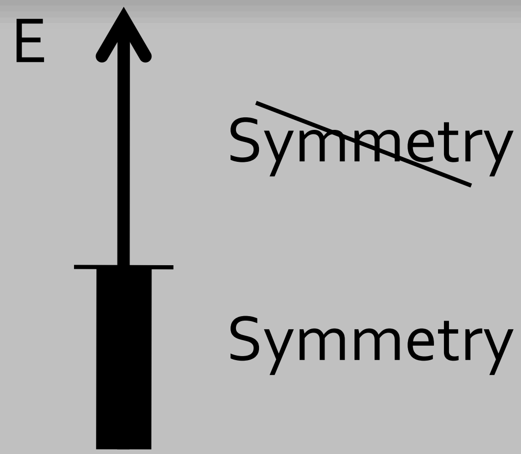
Motivation

Lorentz Invariance is one of the best tested symmetries of nature

From the low-energy perspective, this is perhaps the most pressing issue of any model with LV

The existence of efficient enough mechanisms of Emergent Lorentz Invariance gives credibility to LV

Motivation

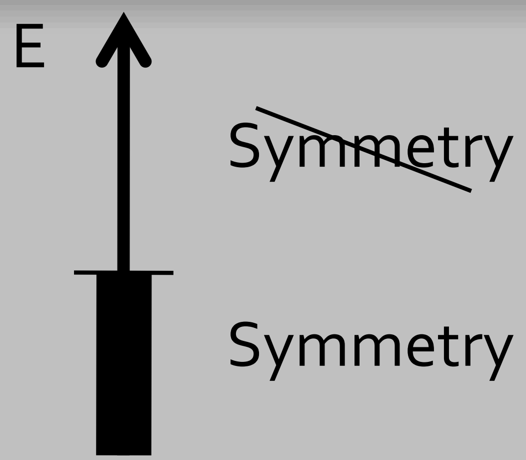


Emergent Symmetry

Implementation:

$$\mathrm{Sym}\left(L\big|_{Dim\,O \leq 4}\right) > \mathrm{Sym}\left(L \right)$$

Motivation



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$$\mathrm{Sym}\left(L\big|_{Dim\, O \leq 4} \right) > \mathrm{Sym}\left(L \right)$$

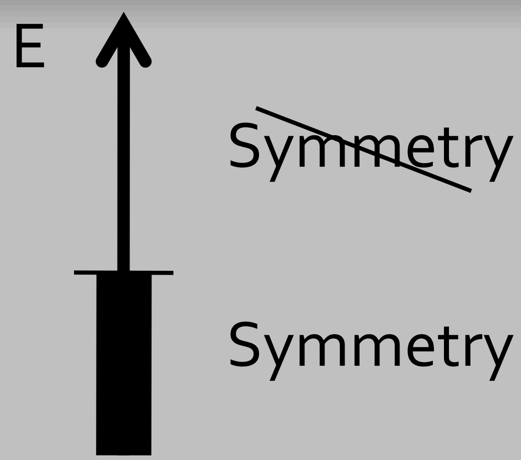
Examples:

- lepton & baryon numbers in SM
- *LI* in single-species *Lifshitz* model

$$\int dt\, d^3x \left\{ (\dot{\phi})^2 + \frac{\phi \Delta^z \phi}{M^{2z-2}} + \mathrm{int} \right\} \qquad z > 1$$

`Anisotropic scaling' in the UV

Motivation



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Implementation:

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Examples:
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$$\int dt\, d^3x \left\{ (\dot{\phi})^2 + c^2 \phi \Delta \phi + \frac{\phi \Delta^z \phi}{M^{2z-2}} + \mathrm{int} \right\}$$

$z > 1$ `Anisotropic scaling' in the UV

Plan

- EFT of Lorentz Violation
- Mechanism 1
- Mechanism 2
- Conclusions

Plan

- EFT of Lorentz Violation

- Mechanism 1 SUSY

- Mechanism 2 Strong Dynamics

- Conclusions

1) EFT of Lorentz Violation

EFT for LV

3 ingredients: LV, gravity, matter

$$L = L^{LV+grav}\left[u_\mu , g_{\mu\nu}\right] + L^{Matter}\left[\psi, g_{\mu\nu}, u_\mu\right]$$

LV: Poincaré $\rightarrow$ $SO(3)\otimes translations$

u_μ dynamical preferred frame *"AETHER"*

timelike vev $\langle u_\mu \rangle = (1,0,0,0)$

LV+Gravity sector

LV+Gravity sector

Is **LV+gravity** "consistent" ? **YES**

Einstein-Aether (2001)

Ghost Condensation (2003)

LV Massive gravity (2004)

Horava Gravity (2009)

Can be viewed as *Gravity in a `Higgs phase'*

Yet, breaking of LI is not *spontaneous*

-> ok with emergence of LI

=> new degrees of freedom

LV+Gravity sector

E.g., *Einstein-Aether* (2001)

$$L^{LV+grav}\left[u_\mu , g_{\mu\nu}\right] = \sqrt{-g}\left[M_P^2 R + M_{LV}^2 (\nabla u)^2 + \lambda (u_\mu u^\mu - 1)\right]$$

bounds on parameters $M \leq 10^{15}\, GeV$ (PPN α_1, α_2)

Matter Sector

Matter Sector

$$L^{Matter}\left[\psi, g_{\mu\nu}, u_\mu\right] = L^{SM}\left[\psi, g_{\mu\nu}\right] + L^{LV}\left[\psi, g_{\mu\nu}, u_\mu\right]$$

"**SME**" of Colladay Kostelecky '98

Matter `mostly' coupled to a universal metric $g_{\mu\nu}$

+ small non-universal direct couplings to u_ν

LI

LV

Matter Sector: *Dim 3*

Example: LV QED

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Example: LV QED

Colladay Kostelecky '98

$$L^{LV\,QED} = \bar{\psi}\left[a\, u_\mu \gamma^\mu + b\, u_\mu \gamma^\mu \gamma^5 + \ldots\right]\psi + A_\mu F_{\nu\rho}\kappa^{\mu\nu\rho}$$ Dim3

(polarized torsion balance '08)

Observational bounds: $b(e^-) < 10^{-26}\, GeV$!

EFT expectation: $b(e^-) \sim M \sim 10^{15}\, GeV$!!!

FINE TUNING

However, CPT forbids all Dim3 LV operators !

CPT+SO(3) => *LI is emergent @ Dim3 in SM* ...

Matter Sector: *Dim 4*

Colladay Kostelecky '98

Example: LV QED

$$\bar{\psi}\left[c_{\mu\nu}\gamma^{\mu} + d_{\mu\nu}\gamma^{5}\gamma^{\mu} + e_{\nu} + f_{\nu}\gamma^{5} + \ldots\right]D^{\nu}\psi + F_{\mu\nu}F_{\rho\sigma}\,\kappa^{\mu\nu\rho\sigma}$$ Dim4

$$c_{\mu\nu} = \delta c\, u_{\mu} u_{\nu}$$

If CPT, only `Sound speeds' remain:

$$\delta c_{\psi}\,\bar{\psi}\gamma^{i}D_{i}\psi \qquad \delta c_{\gamma}\,\vec{B}^{2} \qquad \delta c_{H}\;|D_{i}H|^{2}$$

Matter Sector: *Dim 4*

$\delta c_\psi \, \bar{\psi}\gamma^i D_i \psi$ $\quad\quad$ $\delta c_\gamma^2 \, \vec{B}^2$ $\quad\quad$ $\delta c_H^2 \, |D_i H|^2$

CPT+
Dim4

Observational bounds: $\begin{cases} |c_e - c_\gamma| < 10^{-15} \, ! \\ |c_p - c_\gamma| < 10^{-20} \, !! \end{cases}$

FINE TUNING

EFT expectation: $\delta c \sim 10^{-2} - 10^{-3} \, !!!$

Collins Perez Sudarsky Urrutia Vucetich '04

Iengo Russo Serone '09

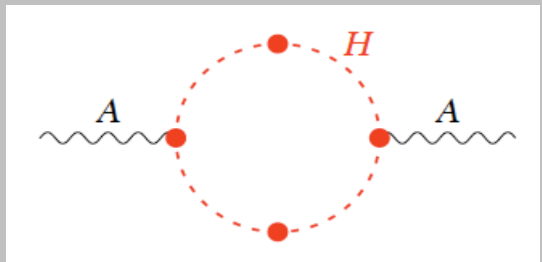
Giudice Strumia Raidal '10

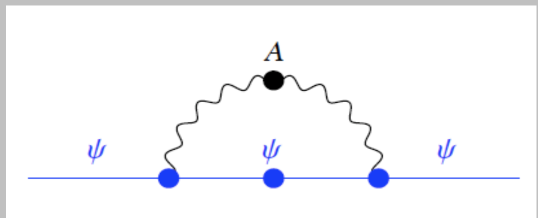
Anber Donoghue '11

Matter Sector: *Dim 4*

(From Giudice Strumia Raidal' 10)

δc's running





$$(4\pi)^2 \frac{d\,c_A}{d\ln\mu} = 2g_A^2 \sum_p b_p(c_A - c_p)$$

$$(4\pi)^2 \frac{d\,c_\psi}{d\ln\mu} = \frac{16}{3}\sum_A g_A^2 C_A(c_\psi - c_A)$$

$$(4\pi)^2 \frac{d\,c_H}{d\ln\mu} = 4\sum_A g_A^2 C_A(c_H - c_A)$$

$$(4\pi)^2 \frac{dg_A}{d\ln\mu} = b_A g_A^3$$

NOTE:

LI-fixed point is IR-attractive !!

Chadha Nielsen' 83

$$\delta c = \left(1 - \beta \log(\mu/M)\right)^{-\frac{B g_0^2}{\beta}} \delta c_0$$

$$g^2 = \frac{g_0^2}{1 - \beta \log(\mu/M)}$$

Matter Sector: *Dim 5,6…*

$$F_{\mu\nu}\,\partial_\lambda\,F_{\rho\sigma}$$

$$w^2 = k^2 + \frac{k^3}{M_1}$$

$$M_1 \geq 10^{18} - 10^{19}\ \ GeV$$

can be forbidden by disctrete symmetries

$$F_{\mu\nu}\,\partial_\lambda\partial_\kappa\,F_{\rho\sigma}$$

$$w^2 = k^2 + \frac{k^4}{M_2^2}$$

$$M_2 \geq 10^{10} - 10^{11}\ \ GeV$$

bounds from MAGIC (AGNs)
Fermi/LAT (GRBs)

via loops, generate: *Dim 3* ops

$$(loop)\,\frac{\Lambda^2}{M_1}\,O_3$$

Dim 4 ops

$$(loop)\,\frac{\Lambda^2}{M_2}\,O_4$$

without LI-emergence mechanism,

LV models may be not ruled out… **neither “ruled in” !**

2) SUSY Mechanism

NR SUSY

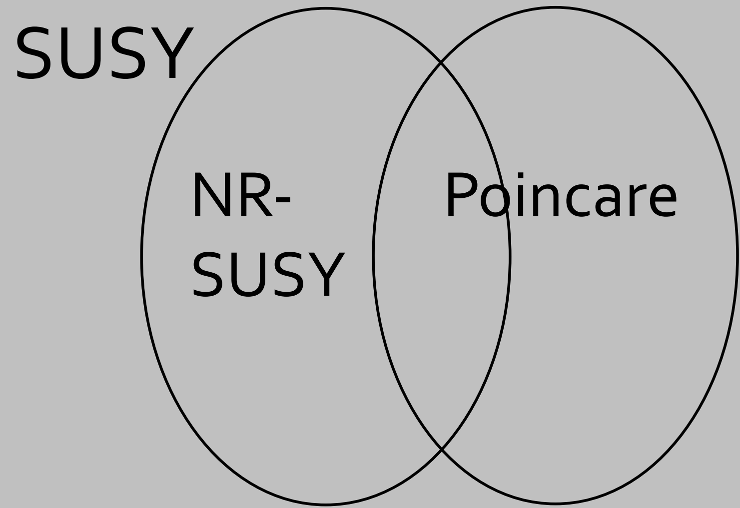
NR-SUSY algebra:

$$\left\{Q,\bar{Q}\right\} = \sigma^0 P_0 + C\,\sigma^i P_i$$

$$\{Q,Q\} = \left\{\bar{Q},\bar{Q}\right\} = [Q,P] = 0$$

$$\cancel{\left\{Q,K_j\right\} = i\sigma_j Q}$$

$$\left\{Q,J_{jk}\right\} = i\sigma_{jk}\,Q$$



Most general SUSY algebra with SO(3) & translations

Parameterized by a universal speed C

The SUSY mechanism

Groot-Nibbelink & Pospelov 04

If $\left\{ \begin{array}{l} \text{NR-SUSY} \\ \text{charged fields} \\ \text{under gauge symm} \end{array} \right\}$ => **ELI @ Dim4**

in particular in the MSSM

Moreover, LV-Dim5,6... suppressed

Proof:

- NR-SUSY => superspace $\left\{ \exp\left(i\, x^{\mu} P_{\mu} + i\theta Q + i\bar{\theta}\bar{Q}\right) \right\}$
- no LV Kahler term with DimO≤4
- only LV Dim4 superpotential term: $\kappa_{IJ} \int d^2\theta\, \Phi_I \partial_0 \Phi_J + h.c.$

-> Not gauge-invariant if Φ_J charged

The SUSY mechanism

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If $\left\{ \begin{array}{l} \text{NR-SUSY} \\ \text{charged fields} \\ \text{under gauge symm} \end{array} \right\}$ => **ELI @ Dim4**

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SUSY-breaking => deviations from LI suppressed $\delta c \sim \left(\frac{m_{soft}}{M} \right)^2$

$$w^2 = (1 + \frac{m^2}{M^2})k^2 + \frac{m^2}{M^3}k^3 + \frac{m^2}{M^4}k^4 + \ldots$$

Obs bounds satisfied with $\boxed{m_{soft} \leq 10^2 TeV}$

=> SUSY at *low* energies!

NR-SUSY & Aether

NR-SUSY with dynamical preferred frame possible?

NR-SUSY & Aether

NR-SUSY with dynamical preferred frame necessary!

NR-SUSY & Aether

OP & Sibiryakov 11

NR-SUSY with dynamical preferred frame necessary!

Breaking LI but not SUSY?

(in Super-Poincare Language)

Impossible with Chiral multiplet

$$\phi(t) \qquad \cancel{H} \Rightarrow \cancel{Q}$$

=> LI broken by (constant) lowest-component of multiplet

Simplest realization:

Chiral vector superfield

$$\bar{D}_{\dot{\alpha}} U^{\mu} = 0$$

Super-aether

$$U^{\mu} = u^{\mu}(y) + \sqrt{2}\theta^{\alpha}\eta_{\alpha}{}^{\mu}(y) + G^{\mu}(y)$$

complex!

aetherino !

Super-Aether

Super-aether Lagrangian @ lowest derivative level OP & Sibiryakov '11

$$L = \int d^2\theta d^2\bar{\theta}\, f(U^\mu \bar{U}_\mu) + \int d^2\theta\,(U^\mu U_\mu - 1)\Lambda$$

Accidental symmetry: SO(3,1) x SO(3,1)$^{\text{internal}}$

LI is emergent even in LV-sector!!

broken by higher order Ops and by gravity

$$c_1 \neq 0\,,\;\; c_2 = c_3 = c_4 = 0$$

Super-Aether

Vacua $u^\mu u_\mu = 1$

Type I $\langle u^\mu \rangle = (\cos\alpha, 0, 0, i\sin\alpha)$

Type II $\langle u^\mu \rangle = (0, 0, \cosh\beta, i\sinh\beta)$

Fluctuations

healthy

ghosty

$v_0 = v_1 = c$

SUSY breaking:

$$\int d^2\theta d^2\bar{\theta}\, g(U^\mu \bar{U}_\mu)\, S$$

$$S_1 = m_1^2 \theta^2 \bar{\theta}^2$$

$$S_2 = m_2^2 (\theta^2 + \bar{\theta}^2)$$

$\mathrm{Im}(u_\mu)$, η_μ partners get stabilized.

Model reduces to Real-Aether with $c_1 >> c_i$

Conclusions – SUSY Mech

- SUSY at ~ 100TeV (or less)

- new states: *aetherons* & *aetherinos*

- spontaneous breaking of isotropy
  –> signatures in inflation?

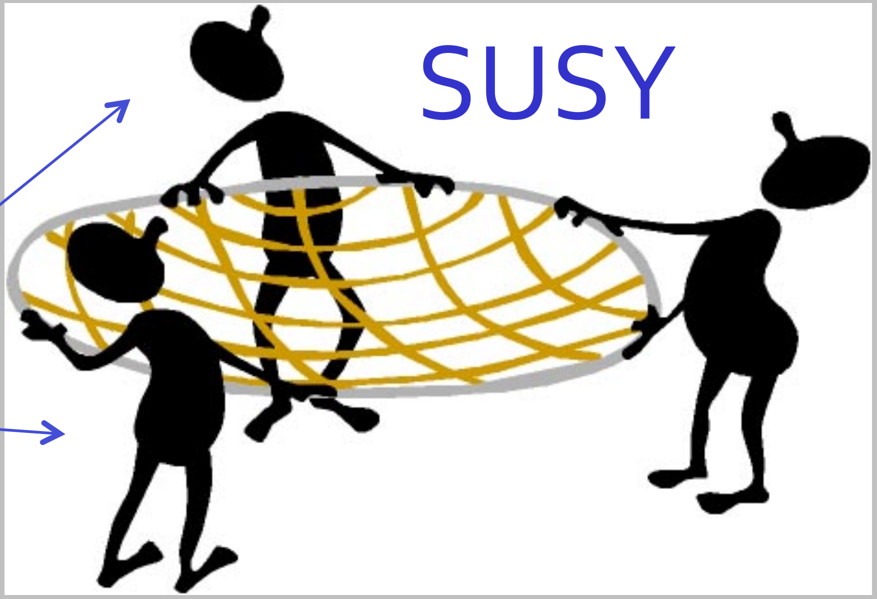
open issues (for the extension to Horava gravity):

- NR-Sugra ?
- Lifshitz-SUSY ?

Redigolo '11

OP & Sibiryakov '11

3) **Strong Dynamics** Mechanism



SUSY
partners

The **Strong Dynamics** mechanism

$\delta c's$ running

$$(4\pi)^2 \frac{d\,\delta c}{d\log\mu} = \beta_{\delta c}\, g^2\, \delta c$$

$$\delta c = \exp\left[\int d(\log\mu)\,\frac{\beta_{\delta c}\, g^2}{(4\pi)^2}\right]\delta c_0$$

For example,

if strongly-coupled fixed point:

$$\delta c = \mu^{\frac{\beta_* g_*^2}{(4\pi)^2}}\,\delta c_0$$

accelerated running

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accelerated running

power > 0 granted: unitarity bound on the dimension Δ_2 of massive spin-2 Op: $\Delta_2 \geq 4$

The **Strong Dynamics** mechanism

Let us test this idea, playing with 3 toys

The **Strong Dynamics** mechanism

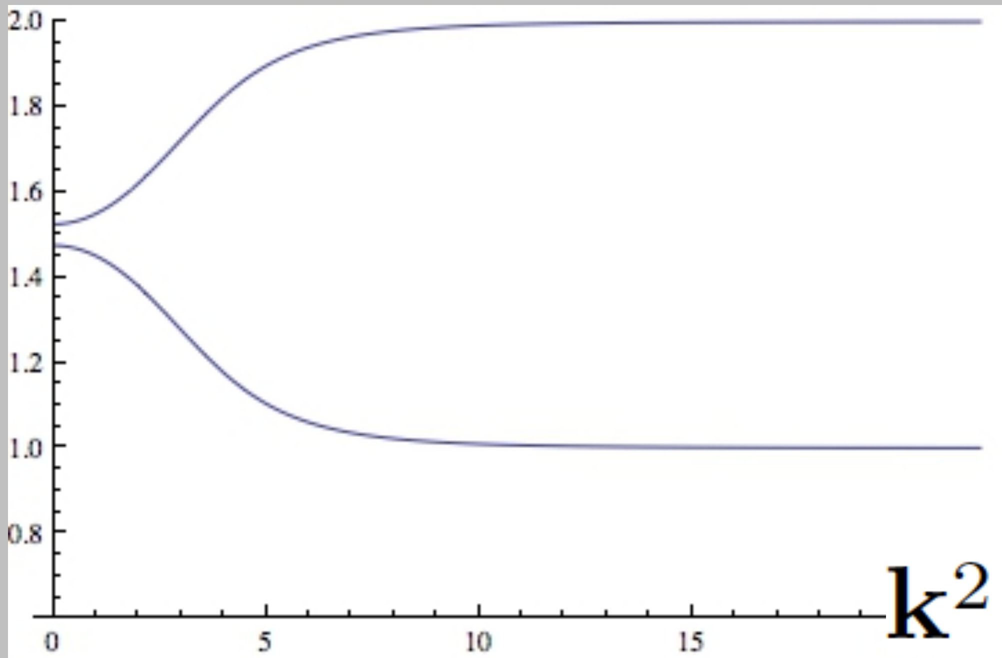
Toy #0: free field theory

The Strong Dynamics mechanism

$$L = \phi(\Box + m^2)\phi + \psi(\Box_c + M^2)\psi + 2\lambda\,\phi\,\psi$$

Dispersion relations:

$$\frac{dw_{\pm}^2}{d\mathbf{k}^2}$$



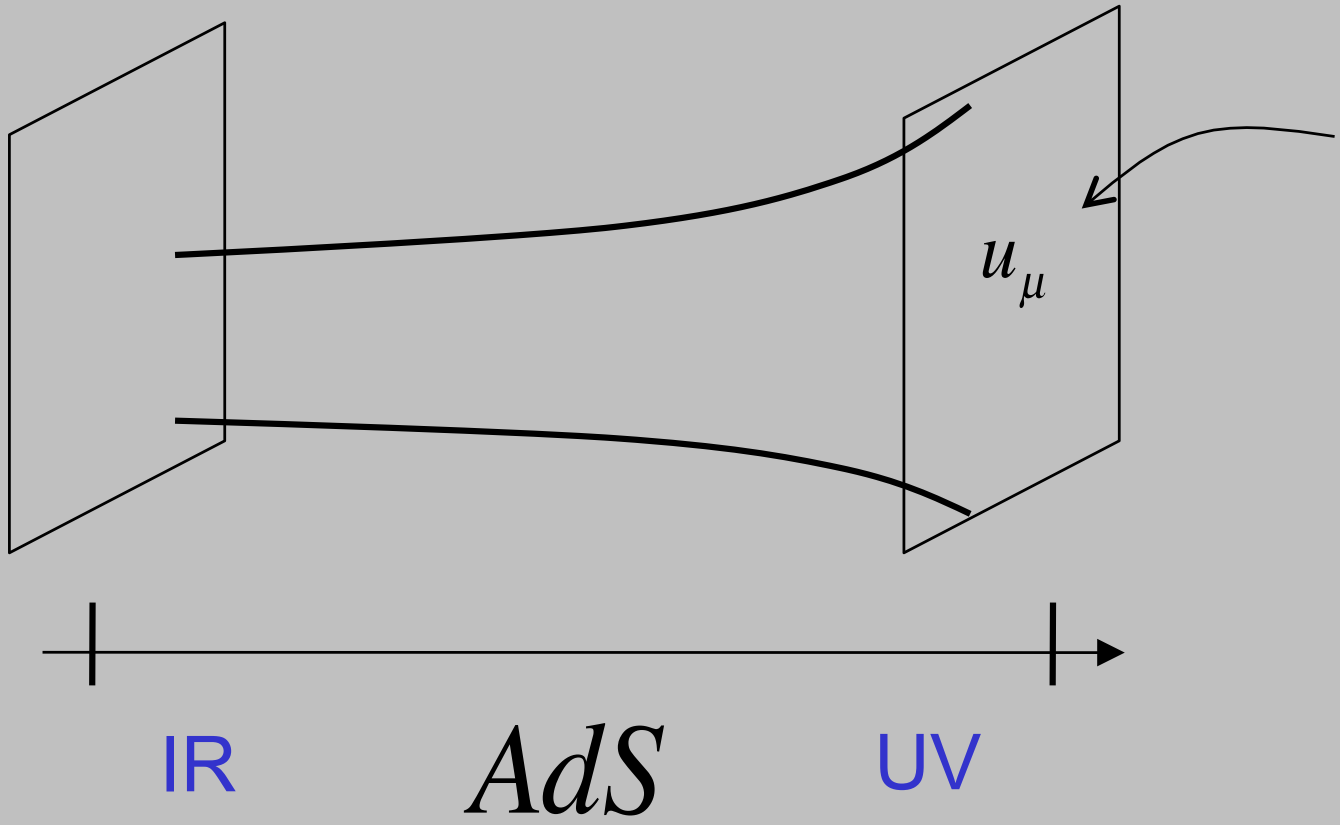
For large λ,

$$c_{\pm}^2(0) \simeq \frac{c^2+1}{2} + O\left(\frac{1}{\lambda}\right)$$

The **Strong Dynamics** mechanism

Toy #1: Randall-Sundrum holography

LV-Randall-Sundrum



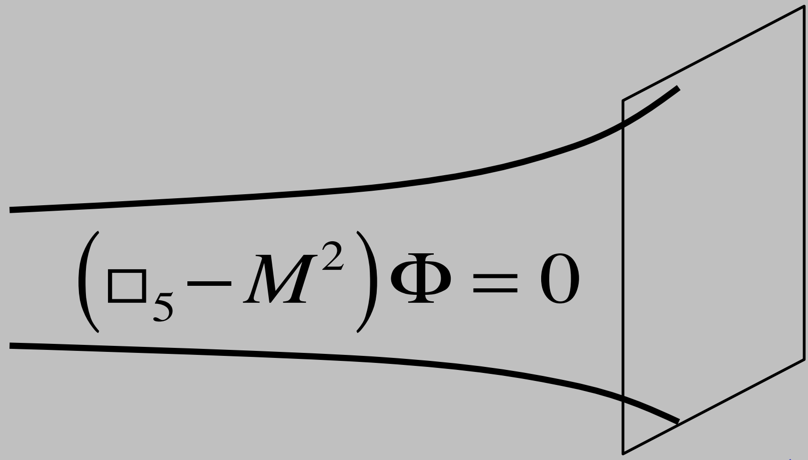
- Lifshitz boundary condition

- Or, simply, Horava gravity on the UV brane!

Dual to a CFT with UV cutoff (coupling to gravity, $M_{Lifshitz}$, M_P)

and IR cutoff (Λ_{QCD}) ←→ RG scale

LV-Randall-Sundrum



$$\left(\Box_5 - M^2\right)\Phi = 0$$

probe scalar

$$\partial_5 \Phi = (w^2 - c^2(k^2)\, k^2)\,\Phi$$

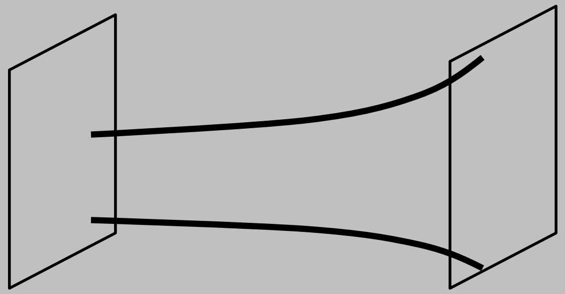
Dim: ***Δ+1***

relevant if Δ < 3

$$L = L_{CFT}(O) + \lambda \phi O - \phi\left(w^2 - c^2 k^2\right)\phi$$

$$G_\phi(w,k)^{-1} \simeq w^2 - c^2 k^2 + \lambda^2 (p^2)^{\Delta-2}$$

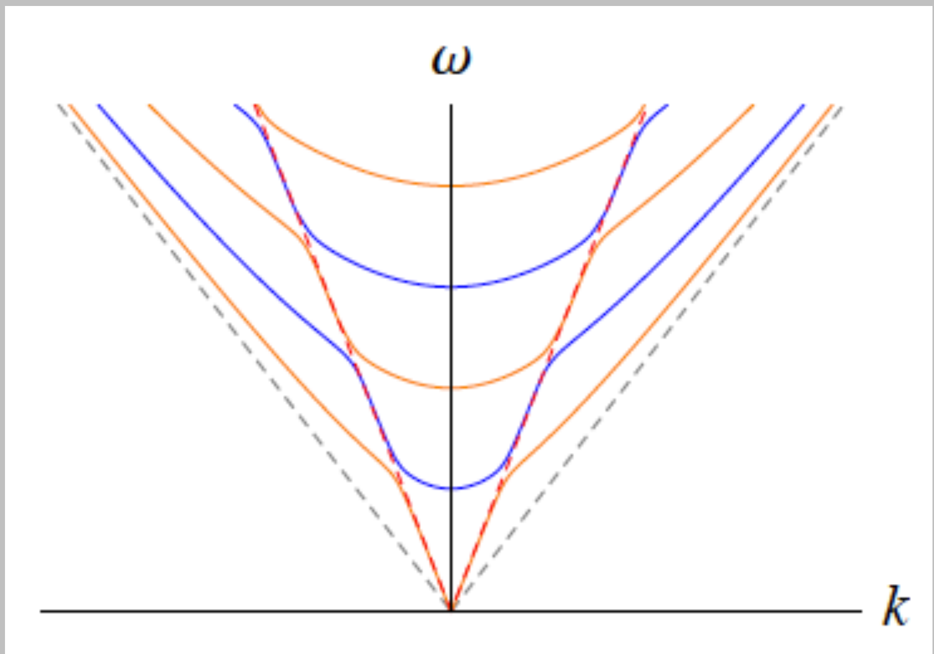
LV-Randall-Sundrum



Λ_{QCD} $\qquad\qquad$ M_L

dispersion relations:

$$w^2 - c^2 k^2 = \lambda^2 \tilde{f}(p)$$



$$\frac{(\Lambda L)^{2(\Delta-3)}}{\lambda^2}(c^2-1)\frac{k^2}{\Lambda^2} = f\left(\frac{p}{\Lambda}\right)$$

running coupling!

(for an operator of Dim *1+Δ*)

LV-Randall-Sundrum

Schematic form of the dispersion relations:

$$w_i^2(k^2) \simeq m_i^2 + \delta c_i^2 k^2 + \sum \frac{k^{2+2n}}{M_{(i,n)}^{2n}}$$

$$\delta c_i^2 \sim \frac{\delta c_{UV}^2}{\lambda^2(\Lambda)}$$

it works!

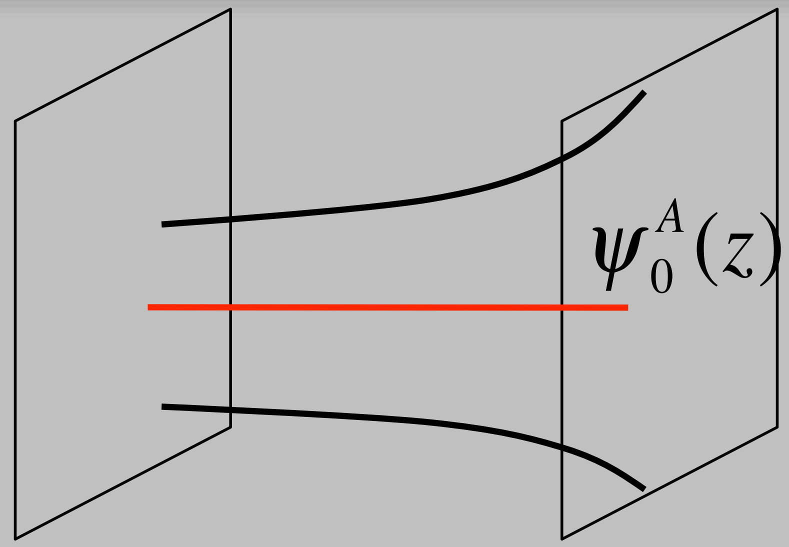
$$\lambda(\Lambda) = \lambda_{UV} \cdot (\Lambda L)^{\Delta - 3} \gg \lambda_{UV}$$

for relevant couplings ($\Delta < 3$)

$$M_{(i,n)} = [\lambda(\Lambda)]^{\frac{n+1}{n}} \Lambda$$

$$\Lambda \ll M_{(i,n)} \le L^{-1}$$

LV-Randall-Sundrum

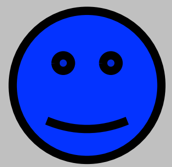


Problem with

gauge fields? A_M

SM gauge fields in the bulk $$\delta c_{IR}^2 \simeq \frac{1}{1-\lambda^2 \log(\Lambda L)} \delta c_{UV}^2$$

~> *weak* gauging of a global symmetry



SM gauge fields on the IR brane

100% composite states

The **Strong Dynamics** mechanism

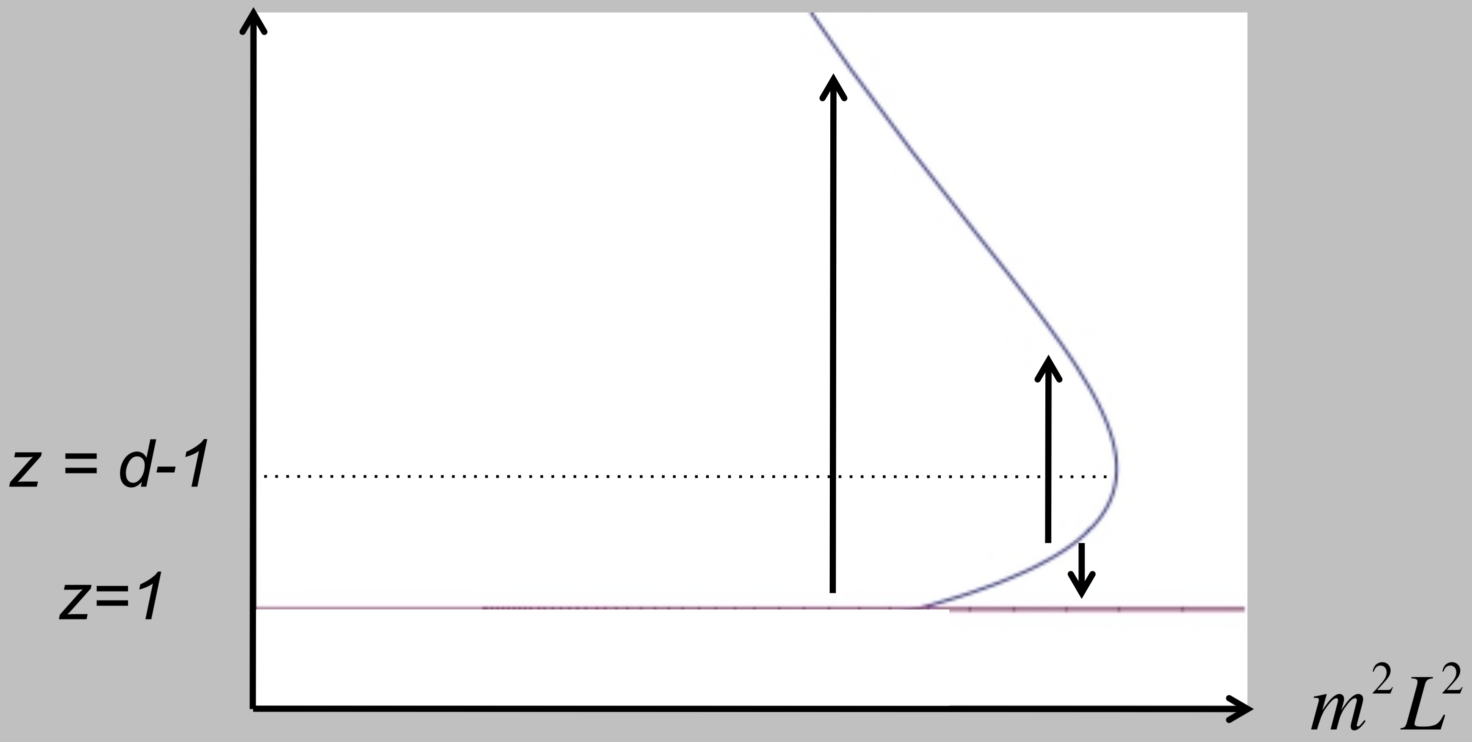
Toy #3: Lifshitz flows

Lifshitz flows

Kachru Liu Mulligan '08

$$ds^2 = \frac{\ell^2}{r^2}dr^2 + \frac{r^2}{\ell^2}d\vec{x}^{\,2} - \frac{r^{2z}}{\ell^{2z}}dt^2 \qquad z > 1$$

Lifshitz solutions in Einstein - Proca - AdS:



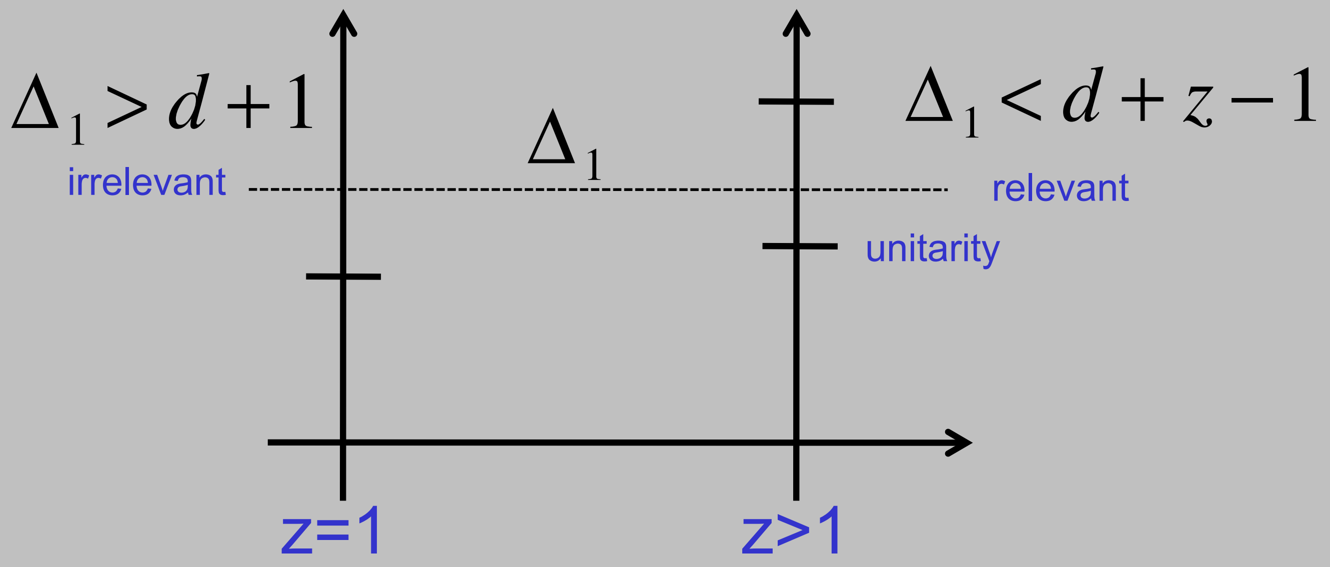
Lifshitz flows

CFT picture:

Lifshitz geom ←→ Lifshitz 'CFT' with spin 1 operator (P frame)

Lifshitz flow ←→ 'CFT' deformed by a *relevant* spin-1 $J_t^{(\Delta_1)} \equiv g(\Lambda)$

flows in the IR to a CFT with an irrelevant op



Lifshitz flows

Propagator of probe scalar operator (no confinement/IR brane)

$$\delta G_\phi(w,k)^{-1} \simeq (p^2)^{\Delta-2}\left[1 + w^2\left(\frac{(p^2)^{(\Delta_1-5)}}{\Lambda_*^{2(\Delta_1-4)}} + \frac{(p^2)^{(\Delta-2)}}{\Lambda_*^{2(\Delta-1)}} + \ldots\right) + \ldots\right]$$

Dispersion relations of bound states (with IR brane)

$$\delta c^2 \simeq \begin{cases} g(\Lambda) \sim (\Lambda L)^{2(\Delta_1-4)} \\ \lambda^{-2}(\Lambda) \sim (\Lambda L)^{\Delta-3} \end{cases}$$

Conclusions – Strong Dyn Mech

compositeness – at low Energies

more strongly tested species -> more composite

Limits on compositeness in SM? $\Lambda \geq (few)\ TeV$

Composite gauge bosons??

How about gravity??

Conclusions

QFT-based mechanismS for Emergence of LI exist

This provides motivation to consider LV models

Very predictive: new physics at *low* energies

Improving LV-tests by 10^4 –> sensitive to emergence

Curious parallel:

EW SSB -> Hierarchy Prob -> Susy/Strong Dyn/...

Lorentz SB -> LV Fine-tuning -> Susy/Strong Dyn/Pospelov&Shang/...?

Thank you!